B17

PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G01N 21/21, G01B 11/06	A1	(11) International Publication Number: WO 99/02970
		(43) International Publication Date: 21 January 1999 (21.01.99)

(21) International Application Number: PCT/US98/11562

(22) International Filing Date: 5 June 1998 (05.06.98)

(30) Priority Data:

08/890,697	11 July 1997 (11.07.97)	US
09/015,839	29 January 1998 (29.01.98)	US

(71) Applicant: THERMA-WAVE, INC. [US/US]; 1250 Reliance Way, Fremont, CA 94539 (US).

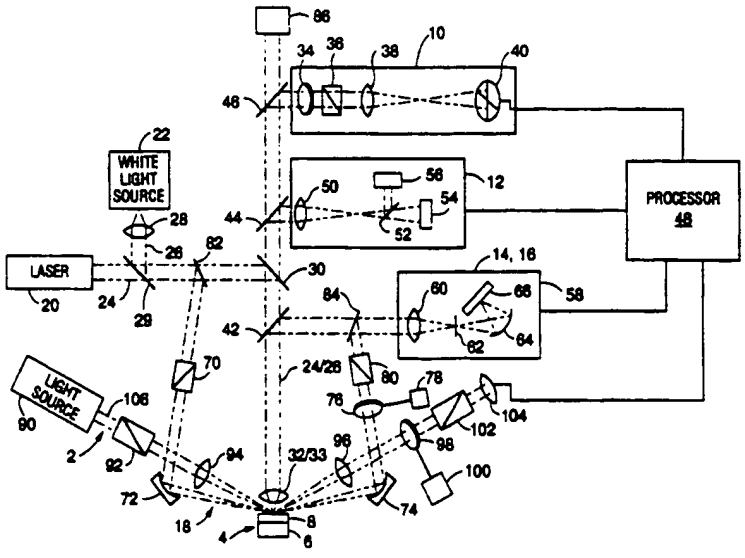
(72) Inventors: ROSENCWAIG, Allan; 3304 Deer Hollow Drive, Danville, CA 94506 (US). OPSAL, Jon; 2295 Norwood Road, Livermore, CA 94550 (US). ASPNES, David, E.; 2517 Olive Chapel Road, Apex, NC 27502 (US). FANTON, Jeffrey, T.; 670 Cuesta Drive, Los Altos, CA 94024 (US).

(74) Agents: STALLMAN, Michael, A. et al.; Limbach & Limbach L.L.P., 2001 Ferry Building, San Francisco, CA 94111 (US).

(81) Designated States: JP, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: AN APPARATUS FOR ANALYZING MULTI-LAYER THIN FILM STACKS ON SEMICONDUCTORS



(57) Abstract

An optical measurement system is disclosed for evaluating samples with multi-layer thin film stacks. The optical measurement system includes a reference ellipsometer and one or more non-contact optical measurement devices. The reference ellipsometer is used to calibrate the other optical measurement devices. Once calibration is completed, the system can be used to analyse multi-layer thin film stacks. In particular, the reference ellipsometer provides a measurement which can be used to determine the total optical thickness of the stack. Using that information coupled with the measurements made by the other optical measurement devices, more accurate information about individual layers can be obtained.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

AN APPARATUS FOR ANALYZING MULTI-LAYER THIN FILM STACKS ON SEMICONDUCTORS

FIELD OF THE INVENTION

The present invention relates to optical analyzers, and more particularly to an optical measurement system having a stable single wavelength ellipsometer and a broadband spectroscopic measurement module to accurately characterize multi-layer thin film stacks.

BACKGROUND OF THE INVENTION

There is considerable interest in developing systems for accurately measuring the thickness and/or composition of multi-layer thin films. The need is particularly acute in the semiconductor manufacturing industry where the thickness of these thin film oxide layers on semiconductor substrates is measured. To be useful, the measurement system must be able to determine the thickness and/or composition of films with a high degree of accuracy. The preferred measurement systems rely on non-contact, optical measurement techniques, which can be performed during the semiconductor manufacturing process without damaging the wafer sample. Such optical measurement techniques include directing a probe beam to the sample, and measuring one or more optical parameters of the reflected probe beam.

In order to increase measurement accuracy and to gain additional information about the target sample, multiple optical measuring devices are often incorporated into a single composite optical measurement system. For example, the present assignee has marketed a product called OPTI-PROBE, which incorporates several optical measurement devices, including a Beam Profile Reflectometer (BPR), a Beam Profile Ellipsometer (BPE), and a Broadband Reflective Spectrometer (BRS). Each of these devices measures parameters of optical beams reflected by the target sample. The BPR and BPE devices utilize technology described in U.S. Patents 4,999,014 and 5,181,080 respectively, which are incorporated herein by reference.

The composite measurement system mentioned above combines the measured results of each of the measurement devices to precisely derive the thickness and composition of the thin film and substrate of the target sample. However, the accuracy of the measured results depends upon precise initial and periodic calibration of the measurement devices in the optical measurement system. Further, recently developed measurement devices have increased sensitivity to more accurately measure thinner films and provide additional information about film and substrate composition. These newer systems require very accurate initial calibration. Further, heat, contamination, optical damage, alignment, etc., that can occur over time in optical measurement devices, affect the accuracy of the measured results. Therefore, periodic calibration is necessary to maintain the accuracy of the composite optical measurement system.

It is known to calibrate optical measurement devices by providing a reference sample having a known substrate, with a thin film thereon having a known composition and thickness. The reference sample is placed in the measurement system, and each optical measurement device measures the optical parameters of the reference sample, and is calibrated using the results from the reference sample and comparing them to the known film thickness and composition. A common reference sample is a "native oxide" reference sample, which is a silicon substrate with an oxide layer formed thereon having a known thickness (about 20 angstroms). After fabrication, the reference sample is kept in a non-oxygen environment to minimize any further oxidation and contamination that changes the thickness of the reference sample film away from the known thickness, and thus reduces the effectiveness of the reference sample for accurate calibration. The same reference sample can be reused to periodically calibrate the measurement system. However, if and when the amount of oxidation or contamination of the reference sample changes the film thickness significantly from the known thickness, the reference sample must be discarded.

For many optical measurement devices, reference samples with known thicknesses have been effective for system calibration. Oxidation and contamination that routinely occurs over time with reference samples is tolerable because the film thickness change resulting from the oxidation/contamination is relatively insignificant compared to the overall thickness of the film (around 100 angstroms). However, new ultra-sensitive optical measurement systems have been recently developed that can measure film layers with thicknesses less than 10 angstroms. These systems require reference samples having film thicknesses on the order of 20 angstroms for accurate calibration. For such thin film reference samples, however, the changes in film layer thickness resulting from even minimal oxidation or contamination are significant compared to the overall "known" film layer thickness, and result in significant calibration error. Therefore, it is extremely difficult, if not impossible, to provide a native oxide reference sample with a known thickness that is stable enough over time to be used for periodic calibration of ultra-sensitive optical measurement systems.

There is a need for a calibration method for ultra-sensitive optical measurement devices that can utilize a reference sample that does not have a stable or known film thickness.

There is also a need in the industry to improve the accuracy of these type of measuring systems to permit characterization of samples having multiple thin film layers formed thereon. More particularly, in the semiconductor industry, semiconductor material substrates are now being fabricated with multiple thin film layers. Each film layer can be formed from a different material. Common layer materials include oxides, nitrides, polysilicon, titanium and titanium-nitride.

Attempts to characterize samples having multiple thin layers with conventional techniques is difficult since each layer has a different thickness and different optical characteristics. The best approaches found to date to characterize such complex stacks is to utilize multiple measurement techniques which generate independent data that can be analyzed by a

processor. Devices now exist which are capable of making both ellipsometric (phase) and spectrophotometric (magnitude) measurements and integrating the results in a microprocessor. The ellipsometers in these devices can include multiple wavelength and multiple angle of incidence measurements. Similarly, the spectrophotometers in some of these devices can be arranged to make measurements at multiple angles of incidence.

While these systems have had reasonable success, further accuracy in analyzing the characteristics of individual layers in a multi-layer stack is always desirable. The subject system, which includes a wavelength stable calibration ellipsometer can be modified to improve the characterization of individual layers of multi-layer thin film stack.

SUMMARY OF THE INVENTION

The present invention is a thin film optical measurement system with a wavelength stable ellipsometer that can be used for calibration and to enhance the characterization of multi-layer thin film stacks. When used for calibration purposes, the stable wavelength ellipsometer functions to precisely determine the thickness of a film on a reference sample. The measured results from the calibration ellipsometer are used to calibrate other optical measurement devices in the thin film optical measurement system. By not having to supply a reference sample with a predetermined known film thickness, a reference sample having a film with a known composition can be repeatedly used to calibrate ultra-sensitive optical measurement devices, even if oxidation or contamination of the reference sample changes the thickness of the film over time.

The calibration reference ellipsometer uses a reference sample that has at least a partially known composition to calibrate at least one other non-contact optical measurement device. The reference ellipsometer includes a light generator that generates a quasi-monochromatic beam of light having a known wavelength and a known polarization for interacting with the reference sample. The beam is directed at a non-normal angle of incidence

relative to the reference sample to interact with the reference sample. An analyzer creates interference between S and P polarized components in the light beam after the light beam has interacted with reference sample. A detector measures the intensity of the light after the beam has passed through the analyzer. A processor determines the polarization state of the light beam entering the analyzer from the intensity measured by the detector. The processor then determines optical properties of the reference sample based upon the determined polarization state, the known wavelength of light from the light generator and the at least partially known composition of the reference sample. The processor operates at least one other non-contact optical measurement device that measures an optical parameter of the reference sample. The processor calibrates the other optical measurement device by comparing the measured optical parameter from the other optical measurement device to the determined optical property from the reference ellipsometer.

The reference ellipsometer has the further benefit in that it can be used to very accurately measure the overall optical thickness of an unknown multi-layer stack on a substrate. In this context, the term total optical thickness refers to the effective thickness of the stack which corresponds to a single uniform layer with uniform optical parameters (i.e. n and k). A stable wavelength ellipsometer is an excellent tool for determining the total optical thickness of a layer or a stack having a thicknesses less than 500 angstroms and is the best tool for stacks having a thickness of 200 angstroms or less.

The reference ellipsometer, which provides only a single wavelength, single angle of incidence output, is not suitable for analyzing the individual layers in a stack. Such analysis requires additional measurements typically from spectroscopic tools such as spectrophotometers and spectroscopic ellipsometers. However, the latter tools alone have difficulty producing sufficient information to accurately characterize the stack.

In accordance with the subject invention, the output from the wavelength stable ellipsometer is used by the processor to determine the overall optical

thickness of the multi-layer stack. This information is used by the processor to reduce the uncertainty of the analysis based on the spectroscopic measurements. By taking a number of measurements at different wavelengths with one or more different techniques, very accurate information about layer composition and thickness can be determined.

Other aspects and features of the present invention will become apparent by a review of the specification, claims and appended figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a plan view of a composite optical measurement system with the calibration ellipsometer of the present invention.

Fig. 2 is a side cross-sectional view of the reflective lens used with the present invention.

Fig. 3 is a plan view of an alternate embodiment of the light source for the calibration ellipsometer of the present invention.

Fig. 4 is a plan view of the composite optical measurement system with multiple compensators in the calibration ellipsometer of the present invention.

Fig. 5 is an illustration of a multi-layer stack on a sample.

Fig. 6 is a flow chart illustrating the steps which can be carried out to characterize individual layers of a multi-layer stack using measurements from both a stable wavelength ellipsometer and a multi-wavelength measurement.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is a composite thin film optical measurement system 1 having a wavelength stable reference ellipsometer 2 that is used, in conjunction with a reference sample 4 having a substrate 6 and thin film 8 with known compositions, to calibrate non-contact optical measurement devices contained in the composite thin film optical measurement system 1.

Figure 1 illustrates the composite optical measurement system 1 that has been developed by the present assignees, which includes five different non-contact optical measurement devices and the reference ellipsometer 2 of the present invention.

Composite optical measurement system 1 includes a Beam Profile Ellipsometer (BPE) 10, a Beam Profile Reflectometer (BPR) 12, a Broadband Reflective Spectrometer (BRS) 14, a Deep Ultra Violet Reflective Spectrometer (DUV) 16, and a Broadband Spectroscopic Ellipsometer (BSE) 18. These five optical measurement devices utilize as few as two optical sources: laser 20 and white light source 22. Laser 20 generates a probe beam 24, and white light source 22 generates probe beam 26 (which is collimated by lens 28 and directed along the same path as probe beam 24 by mirror 29). Laser 20 ideally is a solid state laser diode from Toshiba Corp. which emits a linearly polarized 3 mW beam at 673 nm. White light source 22 is ideally a deuterium-tungsten lamp that produces a 200 mW polychromatic beam that covers a spectrum of 200 nm to 800 nm. The probe beams 24/26 are reflected by mirror 30, and pass through mirror 42 to sample 4.

The probe beams 24/26 are focused onto the surface of the sample with a lens 32 or lens 33. In the preferred embodiment, two lenses 32/33 are mounted in a turret (not shown) and are alternatively movable into the path of probe beams 24/26. Lens 32 is a spherical, microscope objective lens with a high numerical aperture (on the order of 0.90 NA) to create a large spread of angles of incidence with respect to the sample surface, and to create a spot size of about one micron in diameter. Lens 33 is illustrated in Fig. 2, and is a reflective lens having a lower numerical aperture (on the order of 0.4 NA) and capable of focusing deep UV light to a spot size of about 10-15 microns.

Beam profile ellipsometry (BPE) is discussed in U.S. Patent 5,181,080, issued January 19, 1993, which is commonly owned by the present assignee and is incorporated herein by reference. BPE 10 includes a quarter wave

plate 34, polarizer 36, lens 38 and a quad detector 40. In operation, linearly polarized probe beam 24 is focused onto sample 4 by lens 32. Light reflected from the sample surface passes up through lens 32, through mirrors 42, 30 and 44, and directed into BPE 10 by mirror 46. The position of the rays within the reflected probe beam correspond to specific angles of incidence with respect to the sample's surface. Quarter-wave plate 34 retards the phase of one of the polarization states of the beam by 90 degrees. Linear polarizer 36 causes the two polarization states of the beam to interfere with each other. For maximum signal, the axis of the polarizer 36 should be oriented at an angle of 45 degrees with respect to the fast and slow axis of the quarter-wave plate 34. Detector 40 is a quad-cell detector with four radially disposed quadrants that each intercept one quarter of the probe beam and generate a separate output signal proportional to the power of the portion of the probe beam striking that quadrant. The output signals from each quadrant are sent to a processor 48. As discussed in the U.S. 5,181,080 patent, by monitoring the change in the polarization state of the beam, ellipsometric information, such as ψ and Δ, can be determined. To determine this information, the processor 48 takes the difference between the sums of the output signals of diametrically opposed quadrants, a value which varies linearly with film thickness for very thin films.

Beam profile reflectometry (BPR) is discussed in U.S. Patent 4,999,014, issued on March 12, 1991, which is commonly owned by the present assignee and is incorporated herein by reference. BPR 12 includes a lens 50, beam splitter 52 and two linear detector arrays 54 and 56 to measure the reflectance of the sample. In operation, linearly polarized probe beam 24 is focused onto sample 4 by lens 32, with various rays within the beam striking the sample surface at a range of angles of incidence. Light reflected from the sample surface passes up through lens 32, through mirrors 42 and 30, and directed into BPR 12 by mirror 44. The position of the rays within the reflected probe beam correspond to specific angles of incidence with respect to the sample's surface. Lens 50 spatially spreads the beam

two-dimensionally. Beam splitter 52 separates the S and P components of the beam, and detector arrays 54 and 56 are oriented orthogonal to each other to isolate information about S and P polarized light. The higher angles of incidence rays will fall closer to the opposed ends of the arrays. The output from each element in the diode arrays will correspond to different angles of incidence. Detector arrays 54/56 measure the intensity across the reflected probe beam as a function of the angle of incidence with respect to the sample surface. The processor 48 receives the output of the detector arrays 54/56, and derives the thickness and refractive index of the thin film layer 8 based on these angular dependent intensity measurements by utilizing various types of modeling algorithms. Optimization routines which use iterative processes such as least square fitting routines are typically employed. One example of this type of optimization routine is described in "Multiparameter Measurements of Thin Films Using Beam-Profile Reflectivity," Fanton, et. al., Journal of Applied Physics, Vol. 73, No. 11, p.7035, 1993. Another example appears in "Simultaneous Measurement of Six Layers in a Silicon on Insulator Film Stack Using Spectrophotometry and Beam Profile Reflectometry," Leng, et. al., Journal of Applied Physics, Vol. 81, No. 8, page 3570, 1997.

Broadband reflective spectrometer (BRS) 14 simultaneously probes the sample 4 with multiple wavelengths of light. BRS 14 uses lens 32 and includes a broadband spectrometer 58 which can be of any type commonly known and used in the prior art. The spectrometer 58 shown in Fig. 1 includes a lens 60, aperture 62, dispersive element 64 and detector array 66. During operation, probe beam 26 from white light source 22 is focused onto sample 4 by lens 32. Light reflected from the surface of the sample passes up through lens 32, and is directed by mirror 42 (through mirror 84) to spectrometer 58. The lens 60 focuses the probe beam through aperture 62, which defines a spot in the field of view on the sample surface to analyze. Dispersive element 64, such as a diffraction grating, prism or holographic plate, angularly disperses the beam as a function of wavelength to individual

detector elements contained in the detector array 66. The different detector elements measure the optical intensities of the different wavelengths of light contained in the probe beam, preferably simultaneously. Alternately, detector 66 can be a CCD camera, or a photomultiplier with suitably dispersive or otherwise wavelength selective optics. It should be noted that a monochrometer could be used to measure the different wavelengths serially (one wavelength at a time) using a single detector element. Further, dispersive element 64 can also be configured to disperse the light as a function of wavelength in one direction, and as a function of the angle of incidence with respect to the sample surface in an orthogonal direction, so that simultaneous measurements as a function of both wavelength and angle of incidence are possible. Processor 48 processes the intensity information measured by the detector array 66.

Deep ultra violet reflective spectrometry (DUV) simultaneously probes the sample with multiple wavelengths of ultra-violet light. DUV 16 uses the same spectrometer 58 to analyze probe beam 26 as BRS 14, except that DUV 16 uses the reflective lens 33 (Figure 2) instead of focusing lens 32. To operate DUV 16, the turret containing lenses 32/33 is rotated so that reflective lens 33 is aligned in probe beam 26. The reflective lens 33 is necessary because solid objective lenses cannot sufficiently focus the UV light onto the sample.

Broadband spectroscopic ellipsometry (BSE) is discussed in pending U.S. patent application 08/685,606, filed on July 24, 1996, which is commonly owned by the present assignee and is incorporated herein by reference. BSE (18) includes a polarizer 70, focusing mirror 72, collimating mirror 74, rotating compensator 76, and analyzer 80. In operation, mirror 82 directs at least part of probe beam 26 to polarizer 70, which creates a known polarization state for the probe beam, preferably a linear polarization. Mirror 72 focuses the beam onto the sample surface at an oblique angle, ideally on the order of 70 degrees to the normal of the sample surface. Based upon well known ellipsometric principles, the reflected beam will

generally have a mixed linear and circular polarization state after interacting with the sample, based upon the composition and thickness of the sample's film 8 and substrate 6. The reflected beam is collimated by mirror 74, which directs the beam to the rotating compensator 76. Compensator 76 introduces a relative phase delay δ (phase retardation) between a pair of mutually orthogonal polarized optical beam components. Compensator 76 is rotated at an angular velocity ω about an axis substantially parallel to the propagation direction of the beam, preferably by an electric motor 78. Analyzer 80, preferably another linear polarizer, mixes the polarization states incident on it. By measuring the light transmitted by analyzer 80, the polarization state of the reflected probe beam can be determined. Mirror 84 directs the beam to spectrometer 58, which simultaneously measures the intensities of the different wavelengths of light in the reflected probe beam that pass through the compensator/analyzer combination. Processor 48 receives the output of the detector 66, and processes the intensity information measured by the detector 66 as a function of wavelength and as a function of the azimuth (rotational) angle of the compensator 76 about its axis of rotation, to solve the ellipsometric values ψ and Δ as described in U.S. patent application 08/685,606.

Detector/camera 86 is positioned above mirror 46, and can be used to view reflected beams off of the sample 4 for alignment and focus purposes.

In order to calibrate BPE 10, BPR 12, BRS 14, DUV 16, and BSE 18, the composite optical measurement system 1 includes the wavelength stable calibration reference ellipsometer 2 used in conjunction with a reference sample 4. Ellipsometer 2 includes a light source 90, polarizer 92, lenses 94 and 96, rotating compensator 98, analyzer 102 and detector 104.

Light source 90 produces a quasi-monochromatic probe beam 106 having a known stable wavelength and stable intensity. This can be done passively, where light source 90 generates a very stable output wavelength which does not vary over time (i.e. varies less than 1%). Examples of passively stable light sources are a helium-neon laser, or other gas discharge

laser systems. Alternately, a non-passive system can be used as illustrated in Fig. 3 where the light source 90 includes a light generator 91 that produces light having a wavelength that is not precisely known or stable over time, and a monochrometer 93 that precisely measures the wavelength of light produced by light generator 91. Examples of such light generators include solid state lasers, laser diodes, or polychromatic light sources used in conjunction with a color filter such as a grating. In either case, the wavelength of beam 106, which is a known constant or measured by monochrometer 93, is provided to processor 48 so that ellipsometer 2 can accurately calibrate the optical measurement devices in system 1.

The beam 106 interacts with polarizer 92 to create a known polarization state. In the preferred embodiment, polarizer 92 is a linear polarizer made from a quartz Rochon prism, but in general the polarization does not necessarily have to be linear, nor even complete. Polarizer 92 can also be made from calcite. The azimuth angle of polarizer 92 is oriented so that the plane of the electric vector associated with the linearly polarized beam exiting from the polarizer 92 is at a known angle with respect to the plane of incidence (defined by the propagation direction of the beam 106 and the normal to the surface of sample 4). The azimuth angle is preferably selected to be on the order of 30 degrees because the sensitivity is optimized when the reflected intensities of the P and S polarized components are approximately balanced. It should be noted that polarizer 92 can be omitted if the light source 90 emits light with the desired known polarization state.

The beam 106 is focused onto the sample 4 by lens 94 at an oblique angle. For calibration purposes, reference sample 4 ideally consists of a thin oxide layer 8 having a thickness d, formed on a silicon substrate 6. However, in general, the sample 4 can be any appropriate substrate of known composition, including a bare silicon wafer, and silicon wafer substrates having one or more thin films thereon. The thickness d of the layer 8 need not be known, or be consistent between periodic calibrations. The useful light from probe beam 106 is the light reflected by the sample 4

symmetrically to the incident beam about the normal to the sample surface. It is noted however that the polarization state of nonspecularly scattered radiation can be determined by the method of the present invention as well. The beam 106 is ideally incident on sample 4 at an angle on the order of 70 degrees to the normal of the sample surface because sensitivity to sample properties is maximized in the vicinity of the Brewster or pseudo-Brewster angle of a material. Based upon well known ellipsometric principles, the reflected beam will generally have a mixed linear and circular polarization state after interacting with the sample, as compared to the linear polarization state of the incoming beam. Lens 96 collimates beam 106 after its reflection off of the sample 4.

The beam 106 then passes through the rotating compensator (retarder) 98, which introduces a relative phase delay δ (phase retardation) between a pair of mutually orthogonal polarized optical beam components. The amount of phase retardation is a function of the wavelength, the dispersion characteristics of the material used to form the compensator, and the thickness of the compensator. Compensator 98 is rotated at an angular velocity ω about an axis substantially parallel to the propagation direction of beam 106, preferably by an electric motor 100. Compensator 98 can be any conventional wave-plate compensator, for example those made of crystal quartz. The thickness and material of the compensator 98 are selected such that a desired phase retardation of the beam is induced. In the preferred embodiment, compensator 98 is a bi-plate compensator constructed of two parallel plates of anisotropic (usually birefringent) material, such as quartz crystals of opposite handedness, where the fast axes of the two plates are perpendicular to each other and the thicknesses are nearly equal, differing only by enough to realize a net first-order retardation for the wavelength produced by the light source 90.

Beam 106 then interacts with analyzer 102, which serves to mix the polarization states incident on it. In this embodiment, analyzer 102 is another linear polarizer, preferably oriented at an azimuth angle of 45

degrees relative to the plane of incidence. However, any optical device that serves to appropriately mix the incoming polarization states can be used as an analyzer. The analyzer 102 is preferably a quartz Rochon or Wollaston prism. The rotating compensator 98 changes the polarization state of the beam as it rotates such that the light transmitted by analyzer 102 is characterized by:

$$\begin{aligned} I(t) &= (1/2)[\,|E_x|^2(1+\cos^2(\delta/2)+|E_y|^2\sin^2(\delta/2)] \\ &\quad - \mathrm{Im}(E_xE_y^*)\sin\delta\sin(2\omega t) \\ &\quad + \mathrm{Re}(E_xE_y^*)\sin^2(\delta/2)\sin(4\omega t) \\ &\quad + (1/2)(|E_x|^2-|E_y|^2)\sin^2(\delta/2)\cos(4\omega t) \end{aligned} \tag{1}$$

$$= a_0 + b_2\sin(2\omega t) + a_4\cos(4\omega t) + b_4\sin(4\omega t), \tag{2}$$

where E_x and E_y are the projections of the incident electric field vector parallel and perpendicular, respectively, to the transmission axis of the analyzer, δ is the phase retardation of the compensator, and ω is the angular rotational frequency of the compensator.

For linearly polarized light reflected at non-normal incidence from the specular sample, we have

$$E_x = r_p\cos P \tag{3a}$$

$$E_y = r_s\sin P \tag{3b}$$

where P is the azimuth angle of the incident light with respect to the plane of incidence. The coefficients a_0, b_2, a_4, and b_4 can be combined in various ways to determine the complex reflectance ratio:

$$r_p/r_s = \tan\psi e^{i\Delta}. \tag{4}$$

It should be noted that the compensator 98 can be located either between the sample 4 and the analyzer 102 (as shown in Fig. 1), or between the sample 4 and the polarizer 92, with appropriate and well known minor changes to the equations. It should also be noted that polarizer 70, lenses 94/96, compensator 98 and polarizer 102 are all optimized in their construction for the specific wavelength of light produced by light source 90, which maximizes the accuracy of ellipsometer 2.

Beam 106 then enters detector 104, which measures the intensity of the beam passing through the compensator/analyzer combination. The processor 48 processes the intensity information measured by the detector 104 to determine the polarization state of the light after interacting with the analyzer, and therefore the ellipsometric parameters of the sample. This information processing includes measuring beam intensity as a function of the azimuth (rotational) angle of the compensator about its axis of rotation. This measurement of intensity as a function of compensator rotational angle is effectively a measurement of the intensity of beam 106 as a function of time, since the compensator angular velocity is usually known and a constant.

By knowing the composition of reference sample 4, and by knowing the exact wavelength of light generated by light source 90, the optical properties of reference sample 4, such as film thickness d, refractive index and extinction coefficients, etc., can be determined by ellipsometer 2. If the film is very thin, such as less than or equal to about 20 angstroms, the thickness d can be found to first order in d/λ by solving

$$\frac{\rho - \rho_o}{\rho_o} = \frac{4\pi i d \cos\theta}{\lambda} \frac{\epsilon_s(\epsilon_s - \epsilon_o)(\epsilon_o - \epsilon_a)}{\epsilon_o(\epsilon_s - \epsilon_a)(\epsilon_s \cot^2\theta - \epsilon_a)}, \quad (5)$$

where

$$\rho_o = \tan\Psi_o e^{i\Delta_o} \quad (6)$$

$$= \frac{\sin^2\theta - \cos\theta(\epsilon_s/\epsilon_a - \sin^2\theta)^{1/2}}{\sin^2\theta + \cos\theta(\epsilon_s/\epsilon_a - \sin^2\theta)^{1/2}} \quad (7)$$

which is the value of $\rho = \tan\Psi e^{i\Delta}$ for d=0. Here, λ = wavelength of light; and ϵ_s, ϵ_o and ϵ_a are the dielectric functions of the substrate, thin oxide film, and ambient, respectively, and θ is the angle of incidence.

If the film thickness d is not small, then it can be obtained by solving the equations

$$\rho = r_p/r_s, \text{ where} \quad (8)$$

$$r_p = \frac{r_{p,oa} + Zr_{p,so}}{1 + Zr_{p,oa}r_{p,so}} \quad (9)$$

$$r_s = \frac{r_{s,oa} + Zr_{s,so}}{1 + Zr_{s,oa}r_{s,so}} \quad (10)$$

and where

$$Z = e^{2ik\,d}, \quad (11)$$

$$ck_{o\perp}/\omega = n_{o\perp} = (\epsilon_o/\epsilon_a - \sin^2\theta)^{1/2} \quad (12)$$

$$r_{s,so} = \frac{n_{o\perp} - n_{s\perp}}{n_{o\perp} + n_{s\perp}} \quad (13)$$

$$r_{s,oa} = \frac{n_{a\perp} - n_{o\perp}}{n_{a\perp} + n_{o\perp}} \quad (14)$$

$$r_{p,so} = \frac{\epsilon_s n_{o\perp} - \epsilon_o n_{s\perp}}{\epsilon_s n_{o\perp} + \epsilon_o n_{s\perp}} \quad (15)$$

$$r_{p,oa} = \frac{\epsilon_o n_{a\perp} - \epsilon_a n_{o\perp}}{\epsilon_o n_{a\perp} + \epsilon_a n_{o\perp}} \quad (16)$$

and in general

$$n_{j\perp} = (\epsilon_j - \epsilon_a \sin^2\theta)^{1/2}, \quad (17)$$

where j is s or a. These equations generally have to be solved numerically for d and n_o simultaneously, using ϵ_s, ϵ_a, λ, and θ, which are known.

Once the thickness d of film 8 has been determined by ellipsometer 2, then the same sample 4 is probed by the other optical measurement devices BPE 10, BPR 12, BRS 14, DUV 16, and BSE 18 which measure various optical parameters of the sample 4. Processor 48 then calibrates the processing variables used to analyze the results from these optical measurement devices so that they produce accurate results. For each of these measurement devices, there are system variables that affect the measured data and need to be accounted for before an accurate measurement of other samples can be made. In the case of BPE 10, the most significant variable system parameter is the phase shift that occurs due to the optical elements along the BPE optical path. Environmental changes to these optical elements result in an overall drift in the ellipsometric parameter Δ, which then translates into a sample thickness drift calculated by the processor 48 from BPE 10. Using the measured optical parameters of BPE 10 on reference sample 4, and using Equation 5 and the thickness of film 8 as determined from calibration ellipsometer 2, the processor 48 calibrates BPE 10 by deriving a phase offset which is applied to measured results from BPE 10 for other samples, thereby establishing an accurate BPE measurement. For BSE 18, multiple phase offsets are derived for multiple wavelengths in the measured spectrum.

For the remaining measurement devices, BPR 12, BRS 14 and DUV 16, the measured reflectances can also be affected by environmental changes to the optical elements in the beam paths. Therefore, the reflectances R_{ref} measured by BPR 12, BRS 14 and DUV 16 for the reference sample 4 are used, in combination with the measurements by ellipsometer 2, to calibrate these systems. Equations 9-17 are used to calculate the absolute reflectances R^c_{ref} of reference sample 4 from the measured results of ellipsometer 2. All measurements by the BPR/BRS/DUV devices of reflectance (R_s) for any

other sample are then scaled by processor 48 using the normalizing factor in equation 18 below to result in accurate reflectances R derived from the BPR, BRS and DUV devices:

$$R = R_s \, (R^c_{ref}/R_{ref}) \qquad (18)$$

In the above described calibration techniques, all system variables affecting phase and intensity are determined and compensated for using the phase offset and reflectance normalizing factor discussed above, thus rendering the optical measurements made by these calibrated optical measurement devices absolute.

The above described calibration techniques are based largely upon calibration using the derived thickness d of the thin film. However, calibration using ellipsometer 2 can be based upon any of the optical properties of the reference sample that are measurable or determinable by ellipsometer 2 and/or are otherwise known, whether the sample has a single film thereon, has multiple films thereon, or even has no film thereon (bare sample).

The advantage of the present invention is that a reference sample having no thin film thereon, or having thin film thereon with an unknown thickness which may even vary slowly over time, can be repeatedly used to accurately calibrate ultra-sensitive optical measurement devices.

The output of light source 90 can also be used to calibrate the wavelength measurements made by spectrometer 58. The sample 4 can be tipped, or replaced by a tipped mirror, to direct beam 106 up to mirror 42 and to dispersion element 64. By knowing the exact wavelength of light produced by light source 90, processor 48 can calibrate the output of detector 66 by determining which pixel(s) corresponds to that wavelength of light.

It should be noted that the calibrating ellipsometer 2 of the present invention is not limited to the specific rotating compensator ellipsometer

configuration discussed above. The scope of the present invention includes any ellipsometer configuration in conjunction with the light source 90 (having a known wavelength) that measures the polarization state of the beam after interaction with the sample and provides the necessary information about sample 4 for calibrating non-contact optical measurement devices.

For example, another ellipsometric configuration is to rotate polarizer 92 or analyzer 100 with motor 100, instead of rotating the compensator 98. The above calculations for solving for thickness d still apply.

In addition, null ellipsometry, which uses the same elements as ellipsometer 2 of Fig. 1, can be used to determine the film thickness d for calibration purposes. The ellipsometric information is derived by aligning the azimuthal angles of these elements until a null or minimum level intensity is measured by the detector 104. In the preferred null ellipsometry embodiment, polarizers 92 and 102 are linear polarizers, and compensator 98 is a quarter-wave plate. Compensator 98 is aligned so that its fast axis is at an azimuthal angle of 45 degrees relative to the plane of incidence of the sample 4. Polarizer 92 has a transmission axis that forms an azimuthal angle P relative to the plane of incidence, and polarizer 102 has a transmission axis that forms an azimuthal angle A relative to the plane of incidence. Polarizers 92 and 102 are rotated about beam 106 such that the light is completely extinguished (minimized) by the analyzer 102. In general, there are two polarizer 92/102 orientations (P_1, A_1) and (P_2, A_2) that satisfy this condition and extinguish the light. With the compensator inducing a 90 degree phase shift and oriented with an azimuthal angle at 45 degree relative to the plane of incidence, we have:

$$P_2 = P_1 \pm \pi/2 \tag{19}$$

$$A_2 = -A_1 \tag{20}$$

$$\psi = A_1 \geq 0 \tag{21}$$

(where A_1 is the condition for which A is positive).

$$\Delta = 2P_1 + \pi/2 \qquad (22)$$

which, when combined with equations 5-10, allows the processor to solve for thickness d.

Null ellipsometry is very accurate because the results depend entirely on the measurement of mechanical angles, and are independent of intensity. Null ellipsometry is further discussed by R.M.A. Azzam and N.M. Bashara, in *Ellipsometry and Polarized Light* (North-Holland, Amsterdam, 1977); and by D.E. Aspnes, in *Optical Properties of Solids: New Developments*, ed. B.O. Seraphin (North-Holland, Amsterdam, 1976), p. 799.

It is also conceivable to omit compensator 98 from ellipsometer 2, and use motor 100 to rotate polarizer 92 or analyzer 102. Either the polarizer 92 or the analyzer 102 is rotated so that the detector signal can be used to accurately measure the linear polarization component of the reflected beam. Then, the circularly polarized component is inferred by assuming that the beam is totally polarized, and what is not linearly polarized must be circularly polarized. Such an ellipsometer, commonly called a rotating-polarizer or rotating-analyzer ellipsometer, is termed "an incomplete" polarimeter, because it is insensitive to the handedness of the circularly polarized component and exhibits poor performance when the light being analyzed is either nearly completely linearly polarized or possesses a depolarized component. However, using UV light from source 90, the substrate of materials such as silicon contribute enough to the overall phase shift of the light interacting with the sample that accurate results can be obtained without the use of a compensator. In such a case, the same formulas above can be used to derive thickness d, where the phase shift induced by the compensator is set to be zero.

It is to be understood that the present invention is not limited to the embodiments described above and illustrated herein, but encompasses any

and all variations falling within the scope of the appended claims. For example, beams 24, 26, and/or 106 can be transmitted through the sample, where the beam properties (including the beam polarization state) of the transmitted beam are measured. Further, a second compensator can be added, where the first compensator is located between the sample and the analyzer, and the second compensator located between the sample and the light source 90, as illustrated in Fig. 4. These compensators could be static or rotating. In addition, to provide a static or varying retardation between the polarization states, compensator 98 can be replaced by a non-rotating opto-electronic element or photo-elastic element, such as a piezo-electric cell retarder which are commonly used in the art to induce a sinusoidal or static phase retardation by applying a varying or static voltage to the cell.

After the apparatus has been calibrated, it can be used to make a variety of measurements. One type of measurement of significant interest to the semiconductor industry is the characterization of multi-layer thin films on a substrate. Figure 5 is an illustration of such a sample 200. Sample 200 includes a semiconductor substrate 202 which is typically silicon but could be germanium, gallium arsenide, etc. A plurality of thin film layers are deposited on top of the substrate. The thickness of these layers in the illustration has been exaggerated for clarity.

As seen in the example of Figure 5, four thin film layers 204 to 210 are deposited on the stack. The most typical materials used to form thin film layers include oxides, nitrides, polysilicon, titanium and titanium-nitride. Each of these materials have different optical characteristics. As the number and variation of the thin film layers increases, it becomes increasingly difficult to determine characteristics of individual layers even if multiple measurements are taken.

In accordance with the subject invention, the reference ellipsometer of the subject system can further be used to help better analyze complex multi-layer stacks. Although the output from the reference ellipsometer is limited and is not particularly helpful in analyzing individual layers in a stack, it can

be used to provide a very accurate determination of the total optical thickness T of the stack. As discussed below, the processor 48 can use the measurements obtained from the reference ellipsometer in combination with the other measurements to improve the accuracy of the analysis of the individual layers.

Figure 6 is a flow chart illustrating how the system can be configured to analyze multi-layer stacks. The steps shown in Figure 6 would generally occur after calibration in the manner discussed above. In addition, it should be noted that the data gathering steps are shown in sequential order in Figure 6 for illustration purposes only. In fact, the various measurements can be made in any order. The results are stored in the processor as each measurement is completed. When all the desired measurements are completed, then the processor can analyze the data.

In accordance with the subject invention, the ellipsometer 2 is used to measure the test sample (step 230). In this case, the test sample 200 would be placed in the apparatus in place of the reference sample 4 shown in Figure 1. The output from the measurement, in the form of first output signals, would be sent to the processor 48 in step 232.

As noted above, the output of the ellipsometer 2 will be used to calculate the total optical thickness T of the layers. To the extent that the ellipsometer is used for this purpose, it is preferable that the light source 90 be a laser which generates a fixed and known wavelength. In the preferred embodiment, light source 90 is a helium neon laser having a fixed output of 632.8 nanometers. The advantage of the helium neon laser is that it is low in cost, can be tightly focused and generates a known wavelength output regardless of room temperature or power levels.

In accordance with the subject invention, additional measurements must be taken in order to analyze the characteristics of individual layers. In the preferred embodiment, the most desirable measurement will include a multi-wavelength measurement as shown in step 234. This multi-wavelength measurement may be based on either the change in phase or magnitude of a

reflected beam. As noted above, the white light source 22 can be used for either type of measurement. The detector 58 can measure changes in magnitude of the reflected beam across a large wavelength range for either the broadband reflective spectrometer (BRS) 14 or the deep ultraviolet reflective spectrometer (DUV) 16. The detector 58 generates output signals corresponding to a plurality of wavelengths. Step 236 indicates the spectroscopic magnitude measurement.

Changes in phase of the beam at multiple wavelengths can be obtained from the broadband spectroscopic ellipsometer (BSE) 18. Step 238 illustrates the BSE measurement. The second output signals corresponding to the different wavelengths of either type of multi-wavelength measurement are sent to the processor 48 for storage (step 240). In the preferred embodiment, both magnitude and phase measurements are taken and sent to the processor.

Additional measurements are desirable to help more accurately characterize the layers. In the preferred embodiment, these measurements include those taken by the beam profile ellipsometer system (BPE) in step 242 and beam profile reflectometer system (BPR) in step 244. The results from these measurements are sent to the processor in step 246.

In accordance with the subject invention, the processor can use the combination of inputs from the measurement systems to characterize the sample. As noted above, the processor will typically include a modeling algorithm which utilizes an iterative process such as a least squares fitting routine to determine the characteristics of individual layers. (See, for example, the Fanton, et. al. and Leng et. al. articles, cited above). In these types of routines, an initial calculation of the parameters of the stack is made using Fresnel equations and a predetermined "best guess" of layer characteristics. The calculation produces a set of theoretical values which correspond to a set of measurement results that can be obtained using the various test systems in the device. The set of theoretical values are then compared to the set of measurements that were actually obtained from the

various test systems and an evaluation is made as to the closeness or "fit" between the actual and theoretical values. A new "best guess" is then made as to the layer characteristics based on how much and in what manner the theoretical values differed from the measured values. The algorithm recalculates the parameters once again using the Fresnel equations and another comparison is made between the revised theoretical values and the experimentally obtained measurements. This process is continued in an iterative fashion until the theoretical values match the actual measured values to a predetermined level of accuracy.

In accordance with the subject invention, this mathematical modeling is expanded to include parameters representative of the total optical thickness of the stack (step 250). This analysis assumes that the multilayers stack is actually a single layer with common characteristics. The model will generate a set of additional theoretical values corresponding to the measurements which should be generated by the narrow-band, off-axis ellipsometer measurement. During the iterative process, these theoretical values associated with the total optical thickness are compared with actual measured values obtained from the off-axis ellipsometer. The closeness of the "fit" between all of the theoretical values (including the values associated with the total optical thickness) and all of the measured values is evaluated in the iterative process to generate a more accurate analysis of the characteristics of the individual layers in the stack.

The improvements achieved by this approach are derived from the fact that the total optical thickness of a stack can be very accurately determined from measurements using an off-axis ellipsometer with a known wavelength. For stacks ranging up to 200 angstroms thick, this type of measurement can be accurate to within a single angstrom or less.

The subject invention is not limited to the particular algorithm used to derive the characteristics of the individual layers. In addition to the more conventional least square fitting routines, alternative approaches can be used. For example, the high level of computing power now available permits

approaches to be utilized which include genetic algorithms. One example of the use of genetic algorithms to determine the thickness of thin film layers can be found in "Using Genetic Algorithms with Local Search for Thin Film Metrology," Land, et. al., Proceeding of the Seventh International Conference on Genetic Algorithms, July 19-23, page 537, 1997. The only requirement of the subject invention is that the algorithm be designed such that the measurements from the off-axis ellipsometer be used to evaluate the theoretical overall optical thickness of the multilayer stack and that this information be used to help minimize ambiguities in the analysis of the characteristics of the individual layers.

While the subject invention has been described with reference to a preferred embodiment, various changes and modifications could be made therein, by one skilled in the art, without varying from the scope and spirit of the subject invention as defined by the appended claims.

What is claimed is:

1. A method of analyzing a sample having a multiple layer thin film stack thereon comprising the steps of:

measuring the sample using an off-axis ellipsometer which includes a stable narrow band wavelength source and generating first output signals;

measuring the response of the sample to reflected light from a broad band wavelength source and generating a plurality of second output signals corresponding to different wavelengths; and

determining the characteristics of the individual layers on the sample based on the first and second output signals using an algorithm wherein the first output signals are used to provide an accurate measure of the overall optical thickness of the stack in order to improve the accuracy of the analysis of the individual layers.

2. A method as recited in claim 1 wherein the narrow band wavelength source is defined by a gas discharge laser.

3. A method as recited in claim 1 wherein the narrow band wavelength source is defined by a laser diode.

4. A method as recited in claim 1 wherein the narrow band wavelength source is defined by a solid state laser.

5. A method as recited in claim 1 wherein said narrow band wavelength source is linearly polarized prior to striking the sample and wherein the polarization change on reflection is monitored using a rotating compensator and analyzer.

6. A method as recited in claim 1 wherein the step of measuring with a broad band wavelength source includes the step of illuminating the sample with multiple wavelengths of light simultaneously.

7. A method as recited in claim 1 wherein the step of measuring with a broad band wavelength source includes the step of illuminating the sample with multiple wavelengths of light sequentially.

8. A method as recited in claim 1 wherein the step of measuring the sample response to a broad band wavelength source includes analyzing the change in polarization state of the light induced by reflection off the surface of the sample.

9. A method as recited in claim 1 wherein the step of measuring the sample response to a broad band wavelength source includes analyzing the change in magnitude of the light induced by reflection off the surface of the sample.

10. A method as recited in claim 1 wherein the step of measuring the sample response to a broad band wavelength source includes light spanning a wavelength range of 200nm to 800nm.

11. A method as recited in claim 1 further including the step of measuring the response of the sample to reflected light at one or more wavelengths and at a plurality of different angles of incidence and generating third output signals and using the third output signals to further characterize the individual layers on the sample.

12. A method of determining the characteristics of individual layers in a thin film stack formed on a sample comprising the steps of:

generating a first probe beam defined by quasi-monochromatic light of a known wavelength;

directing the first probe beam to reflect off the surface of the sample at a non-normal angle of incidence;

analyzing the change in polarization state of the first probe beam induced by the interaction with the sample and generating first output signals in response thereto;

generating a second probe beam from a broad band wavelength source;

directing said second probe beam to reflect off the surface of the sample;

monitoring the second probe beam after reflection from the sample and determining either a phase or magnitude thereof at a plurality of wavelengths and generating a plurality of second output signals corresponding thereto; and

determining the characteristics of the individual layers on the sample based on the first and second output signals using an algorithm wherein the first output signals are used to provide an accurate measure of the overall optical thickness of the stack in order to improve the accuracy of the analysis of the individual layers.

13. A method as recited in claim 12 wherein said second probe beam is directed to the surface of the sample in a manner such that multiple wavelengths of light strike the surface simultaneously.

14. A method as recited in claim 12 wherein said second probe beam is directed to the surface of the sample in a manner such that multiple wavelengths of light strike the surface of the sample sequentially.

15. A method as recited in claim 12 wherein said step of monitoring the second probe beam includes analyzing the change in polarization state of the beam induced by reflection off the surface of the sample.

16. A method as recited in claim 12 wherein said step of monitoring the second probe beam includes analyzing the change in magnitude of the beam induced by reflection off the surface of the sample

17. A method as recited in claim 12 wherein the first probe beam is generated by a gas discharge laser.

18. A method as recited in claim 12 wherein the first probe beam is generated by a laser diode.

19. A method as recited in claim 12 wherein the first probe beam is generated by a solid state laser.

20. A method as recited in claim 12 wherein the light in said first probe beam is linearly polarized prior to striking the sample and wherein the polarization change on reflection is monitored using a rotating compensator and analyzer.

21. A method as recited in claim 12 wherein the broad band wavelength source includes light spanning a wavelength range of 200nm to 800nm.

22. A method as recited in claim 12 further including the step of measuring the response of the sample to reflected light at one or more wavelengths and at a plurality of different angles of incidence and generating third output signals and using the third output signals to further characterize the individual layers on the sample.

23. An apparatus for characterizing thin film layers in a stack formed on a sample comprising:

an off-axis ellipsometer, said ellipsometer having a quasi-monochromatic source for generating a first probe beam of a known wavelength, said ellipsometer for measuring the change in polarization state of the first probe beam after reflection from the sample and generating first output signals corresponding thereto;

a broad band light source for generating a second probe beam;

a detector system for monitoring either the phase or magnitude changes of the second probe beam after interacting with the sample and generating a plurality of second output signals corresponding to a plurality of different wavelengths; and

processor for determining the characteristics of the individual layers on the sample based on the first and second output signals, said processor using an algorithm wherein the first output signals are used to provide an accurate measure of the overall optical thickness of the stack in order to improve the accuracy of the analysis of the individual layers.

24. An apparatus as recited in claim 23 wherein said second probe beam is directed to the surface of the sample in a manner such that multiple wavelengths of light strike the surface simultaneously.

25. An apparatus as recited in claim 23 wherein said second probe is directed to the surface of the sample in a manner such that multiple wavelengths of light strike the surface of the sample sequentially

26. An apparatus as recited in claim 23 wherein the detector system analyzes the change in polarization state of the second probe beam induced by reflection off the surface of the sample.

27. An apparatus as recited in claim 23 wherein the detector system analyzes the change in magnitude of the second probe beam induced by reflection off the surface of the sample.

28. An apparatus as recited in claim 23 wherein the detector system analyzes both the change in polarization state of the second probe beam induced by reflection off the surface of the sample and the change in magnitude of the second probe beam induced by reflection off the surface of the sample and wherein the processor uses the output signals generated by both measurements to further characterize the sample.

29. An apparatus as recited in claim 23 wherein the quasi-monochromatic source is defined by a gas discharge laser.

30. An apparatus as recited in claim 23 wherein the quasi-monochromatic source is defined by a helium-neon laser.

31. An apparatus as recited in claim 23 wherein the quasi-monochromatic source is defined by a solid state laser.

32. An apparatus as recited in claim 23 wherein the quasi-monochromatic source is defined by a laser diode.

33. An apparatus as recited in claim 23 wherein the light in said first probe beam is linearly polarized prior to striking the sample and wherein the polarization change on reflection is monitored using a rotating compensator and analyzer.

34. An apparatus as recited in claim 23 wherein the broad band wavelength source includes light spanning a wavelength range of 200nm to 800nm.

35. An apparatus as recited in claim 23 wherein the detector system further includes the step of measuring the response of the sample to reflected light at one or more wavelengths and at a plurality of different angles of incidence and generating third output signals and using the third output signals to further characterize the individual layers on the sample.

36. An apparatus as recited in claim 35 wherein said light which is measured at a plurality of different angles of incidence is generated by a laser.

37. The reference ellipsometer of claim 23, wherein the quasi-monochromatic source produces light having a stable known wavelength to within 1 percent.

38. An optical apparatus for evaluating characteristics of a semiconductor test sample comprising:

a spectroscopic measurement module including a broadband light source for creating a probe beam directed to reflect off the test sample and including a detector for monitoring changes in either the polarization or magnitude of the reflected probe beam at multiple wavelengths;

a processor for evaluating the test sample based on the measured changes of the probe beam; and

a calibration module including a reference sample and an off-axis ellipsometer having a wavelength stable, narrowband light source for measuring the reference sample and wherein said apparatus is arranged so that the reference sample is also measured by the spectroscopic module and wherein the processor utilizes the measurements of the reference sample by both the off-axis ellipsometer and the spectroscopic module to calibrate the spectroscopic module for subsequent measurements of test samples.

39. An apparatus as recited in claim 38 wherein said spectroscopic module is a spectrophotometer wherein the changes in magnitude of the reflected probe beam are measured at a plurality of wavelengths.

40. An apparatus as recited in claim 38 wherein said spectroscopic module is a spectroscopic ellipsometer wherein changes in the polarization state of the probe beam are analyzed at a plurality of wavelengths.

41. An apparatus as recited in claim 38 wherein the narrowband light source is defined by a gas discharge laser.

42. An apparatus as recited in claim 41 wherein said gas discharge laser is a helium-neon laser.

43. An apparatus as recited in claim 38 wherein said narrowband light source is defined by a laser diode.

44. An apparatus as recited in claim 38 wherein the narrowband wavelength source produces light have a stable known wavelength to within one percent.

45. An apparatus as recited in claim 38 wherein the reference sample is defined by a substrate having an oxide layer thereon wherein the composition of the oxide is known prior to measurement while the thickness of the oxide layer is unknown prior to measurement.

46. A method of operating a spectroscopic apparatus to analyze the characteristics of a semiconductor test sample, wherein the spectroscopic apparatus includes a broadband light source for creating a probe beam directed to reflect off the test sample and including a detector to monitor changes in either the polarization or magnitude of the reflected probe beam

at a plurality of wavelengths, said spectroscopic apparatus further including a calibration module incorporating an off-axis ellipsometer having a stable wavelength narrowband light source, said calibration module further including a reference sample, said method comprising the steps of:

measuring the reference sample with the narrowband light source of the off-axis ellipsometer;

measuring the reference sample with the broadband light source of the spectroscopic apparatus;

analyzing the characteristics of the reference sample using the measurements obtained from both the off-axis ellipsometer and spectroscopic apparatus;

comparing the analyses of the characteristics of the reference sample derived from measurements obtained from the off-axis ellipsometer and the spectroscopic apparatus;

calibrating the spectroscopic apparatus based on the comparison of the analyses of the characteristics of the reference sample; and

measuring and analyzing a test sample with the calibrated spectroscopic apparatus.

47. A method as recited in claim 46 wherein the spectroscopic apparatus operates to measure changes in the magnitude of the reflected probe beam at a plurality of wavelengths.

48. A method as recited in claim 46 wherein the spectroscopic apparatus operates to measure changes in the polarization state of the probe beam at a plurality of wavelengths.

49. A method as recited in claim 46 wherein the reference sample is defined by a substrate having an oxide layer thereon.

50. A method as recited in claim 49 wherein during said step of analyzing the reference sample, the thickness of the oxide layer of the reference sample determined based on the measurements made with the spectroscopic apparatus is compared with the thickness of the oxide layer determined based on the measurements made with the off-axis ellipsometer in order to calibrate the spectroscopic apparatus.

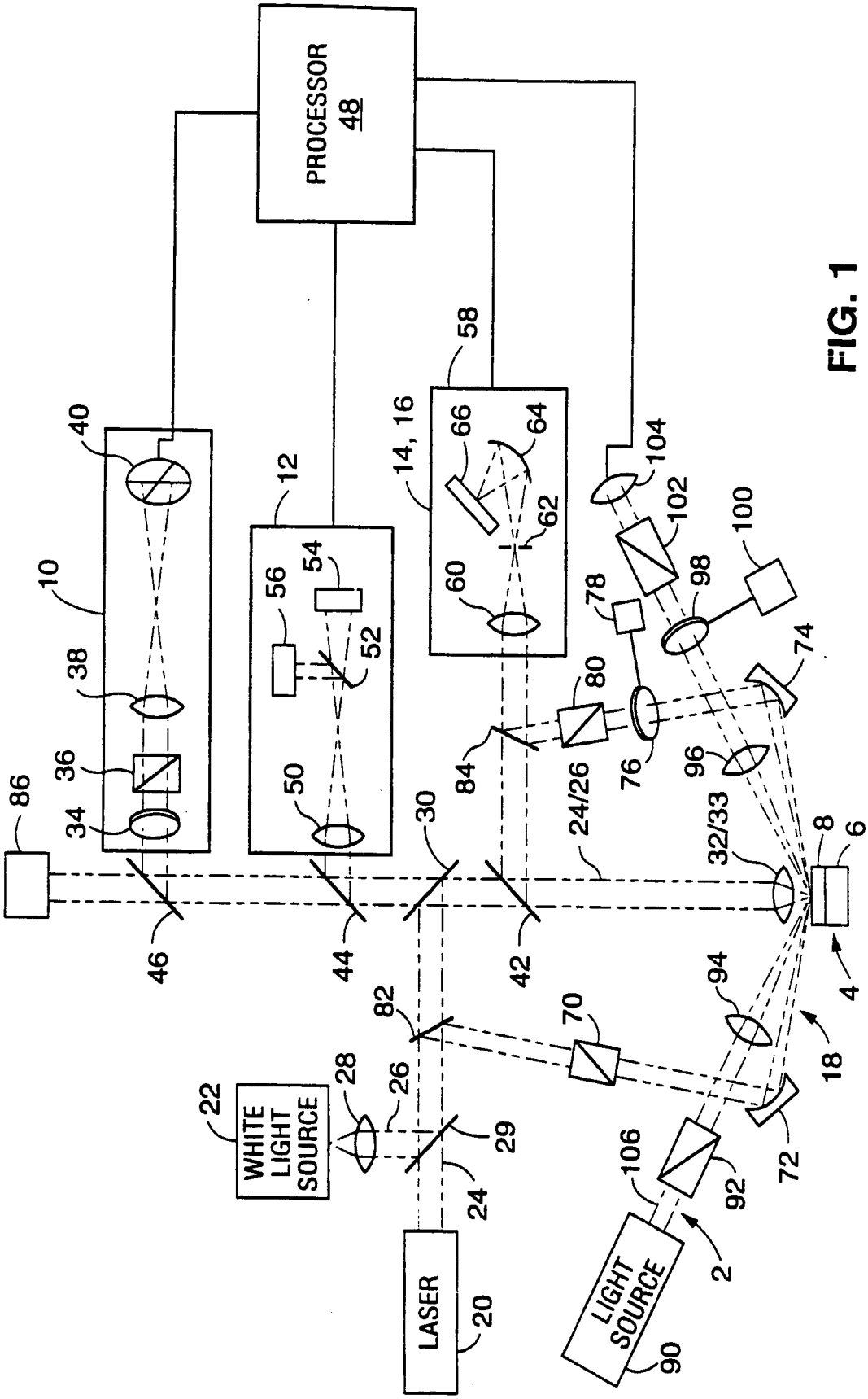

PROCESSOR
48
WHITE LIGHT SOURCE
LASER
LIGHT SOURCE
10
12
14, 16
18
20
22
24
24/26
26
28
29
30
32/33
34
36
38
40
42
44
46
50
52
54
56
58
60
62
64
66
70
72
74
76
78
80
82
84
86
90
92
94
96
98
100
102
104
106
2
4
6
8

FIG. 1

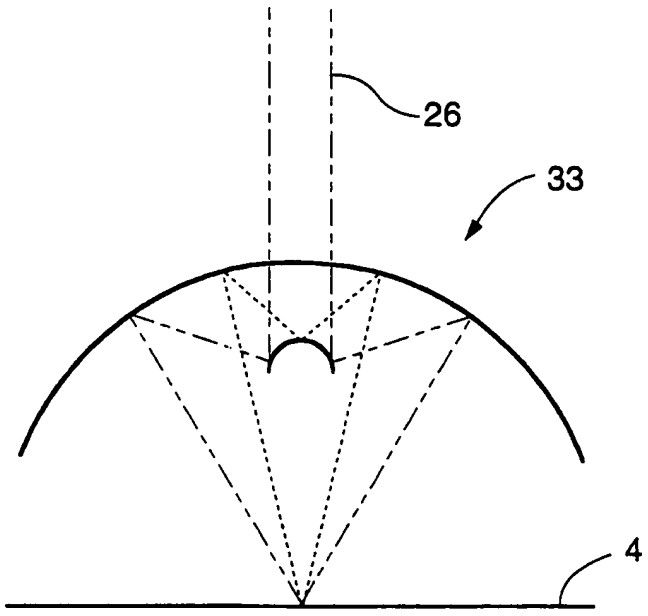


FIG. 2

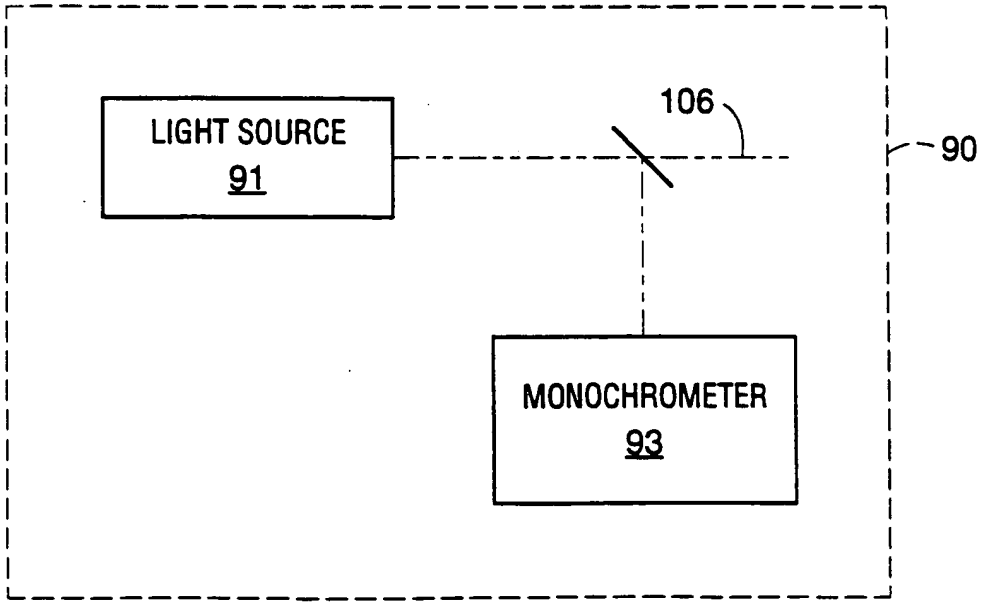


FIG. 3

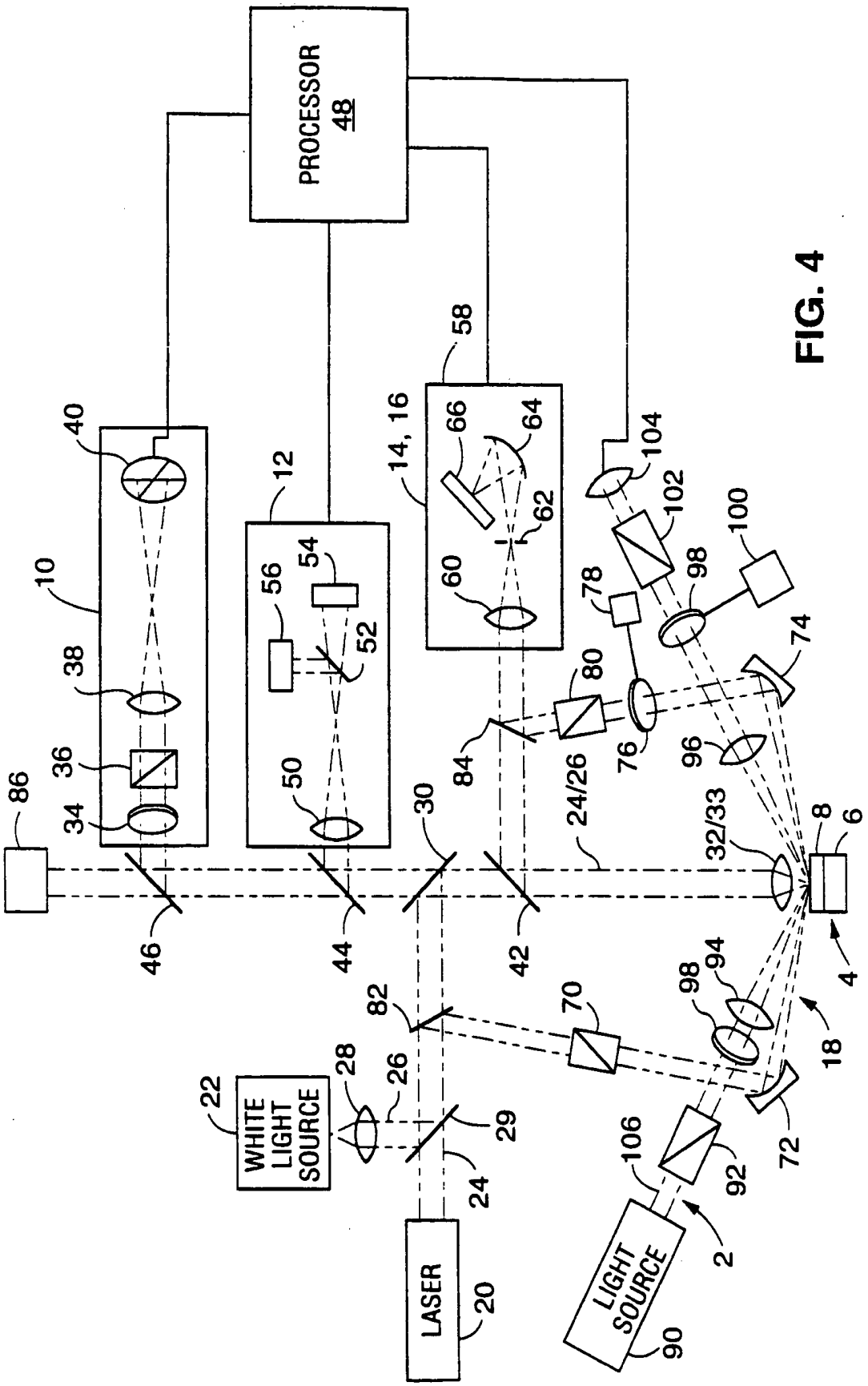

PROCESSOR
48
WHITE LIGHT SOURCE
LASER
LIGHT SOURCE
10
12
14, 16
18
20
22
24
24/26
26
28
29
30
32/33
34
36
38
40
42
44
46
50
52
54
56
58
60
62
64
66
70
72
74
76
78
80
82
84
86
90
92
94
96
98
100
102
104
106
2
4
6
8

FIG. 4

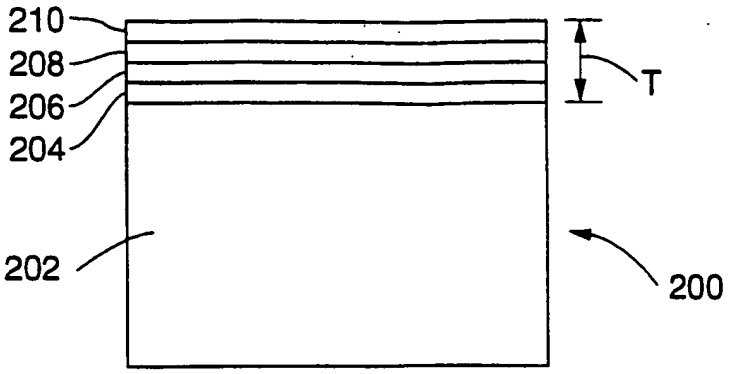

210
208
206
204
202
T
200

FIG. 5

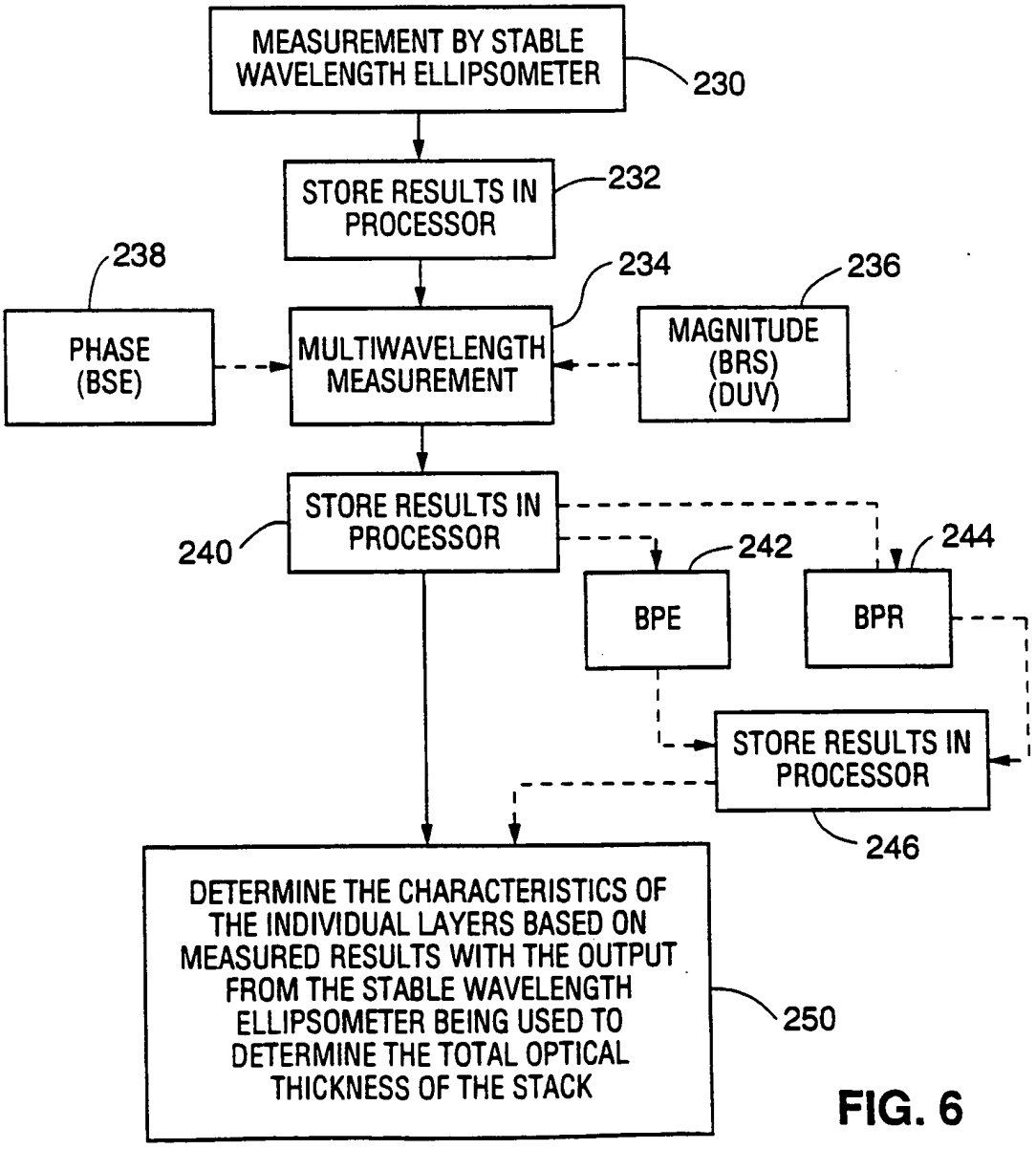

MEASUREMENT BY STABLE WAVELENGTH ELLIPSOMETER
230
STORE RESULTS IN PROCESSOR
232
238
234
236
PHASE (BSE)
MULTIWAVELENGTH MEASUREMENT
MAGNITUDE (BRS) (DUV)
STORE RESULTS IN PROCESSOR
240
242
244
BPE
BPR
STORE RESULTS IN PROCESSOR
246
DETERMINE THE CHARACTERISTICS OF THE INDIVIDUAL LAYERS BASED ON MEASURED RESULTS WITH THE OUTPUT FROM THE STABLE WAVELENGTH ELLIPSOMETER BEING USED TO DETERMINE THE TOTAL OPTICAL THICKNESS OF THE STACK
250

FIG. 6

INTERNATIONAL SEARCH REPORT

Int. ational Application No
PCT/US 98/11562

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01N21/21 G01B11/06

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 581 350 A (CHEN) 3 December 1996 see column 1, line 6 - line 10 see column 14, line 37 - line 46 see column 22, line 10 - column 23, line 15; figure 12 ---	1,12,23, 38,46
A	US 5 608 526 A (PIWONKA-CORLE) 4 March 1997 see column 1, paragraph 1 see column 8, line 62 - column 9, line 4 see column 19, line 61 - column 20, line 16; figure 4 ---	1,12,23, 38,46
A	WO 96 12941 A (THERMA-WAVE) 2 May 1996 --- -/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 September 1998	24/09/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Thomas, R.M.

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Inte...ational Application No
PCT/US 98/11562

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 396 409 A (THERMA-WAVE) 7 November 1990 & US 4 999 014 A cited in the application	
A	EP 0 503 874 A (THERMA-WAVE) 16 September 1992	
A	US 5 181 080 A (THERMA-WAVE) 19 January 1993 cited in the application	

1

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5581350 A	03-12-1996	NONE	
US 5608526 A	04-03-1997	NONE	
WO 9612941 A	02-05-1996	EP 0787286 A	06-08-1997
		JP 10507833 T	28-07-1998
		US 5596411 A	21-01-1997
EP 0396409 A	07-11-1990	US 4999014 A	12-03-1991
		US 5042951 A	27-08-1991
		DE 69017947 D	27-04-1995
		DE 69017947 T	16-11-1995
		DE 69032110 D	16-04-1998
		EP 0397388 A	14-11-1990
		JP 1968077 C	18-09-1995
		JP 3205536 A	09-09-1991
		JP 6103252 B	14-12-1994
		JP 2514099 B	10-07-1996
		JP 3017505 A	25-01-1991
EP 0503874 A	16-09-1992	US 5159412 A	27-10-1992
		JP 5107035 A	27-04-1993
US 5181080 A	19-01-1993	DE 69222742 D	20-11-1997
		DE 69222742 T	20-05-1998
		EP 0549166 A	30-06-1993
		JP 5248826 A	28-09-1993